N73-18036
NASA CR-112262

A STUDY OF THE EFFECTS OF AEROELASTIC DIVERGENCE ON THE WING STRUCTURE OF AN OBLIQUE-WING SUPERSONIC TRANSPORT CONFIGURATION

by the

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January 1973

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Langley Research Center
Contract NAS1-10900

FOREWORD

The work described herein was conducted by the Hampton Technical Center of LTV Aerospace Corporation, under NASA Advanced Transport Technology Project Manager, Mr. W. J. Alford, Jr. The Research Direction of this work was provided by Mr. R. C. Goetz of the Langley Research Center Loads Division, and Technical Coordination by Mr. J. D. Pride, Jr., and Mr. L. C. Forrest of the Langley Research Center Systems Engineering Division. The report was prepared by R. E. Calleson under the direction of R. R. Lynch, the Hampton Technical Center Advanced Aircraft Technology Manager.

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SUMMARY

Transport aircraft configured with an oblique-wing may realize certain advantages, particularly improved performance, when flying at supersonic speeds. However, the forward swept portion of the wing is susceptible to aeroelastic divergence. Aspect ratio is one of the critical parameters that affects the structural requirements necessary to avoid aeroelastic divergence. This report indicates the sensitivity to aspect ratio for an arbitrary transport size using two wing thickness ratios. A relatively low aspect ratio appears necessary for an oblique-wing when constructed of conventional aluminum alloy materials. The aspect ratio may be increased by increasing the wing thickness ratio and by utilizing materials with higher moduli of elasticity and rigidity.

INTRODUCTION

A long narrow straight wing positioned obliquely to the direction of flight (see figure 1) is potentially more efficient at supersonic speeds than the conventional swept wing, Reference 1. The continuous wing panel also adapts itself more readily to varying angles of obliquity and, hence, to varying flight speeds. However, the forward swept half of an oblique wing is susceptible to aeroelastic divergence. This report presents a preliminary study of the effects on structural stiffness requirements of the wing box to avoid aeroelastic divergence for a 200,000 pound transport type airplane flying at low supersonic speeds. A single fuselage with wing obliquity of 45 degrees is assumed (reference figure 1).

For a given dynamic pressure and wing aspect ratio, certain stiffness requirements must be met to prevent aeroelastic divergence and subsequent structural failure. Increases in either the dynamic pressure or aspect ratio increases the required stiffness. The available stiffness is limited by the wing box thickness and material. For a given thickness ratio, an increase in aspect ratio not only increases the bending moment, but decreases the wing box thickness. Therefore, it is apparent that there are limits in aspect ratio to meet the required bending stiffness. The purpose of this study is to define the upper limits of aspect ratio for two wing thickness ratios. The method is based on the required bending stiffness to prevent divergence and is compared with the available bending stiffness of a solid wing box section. In addition, the bending stiffness associated with typical maneuver load strength design criteria is presented to show that the stiffness resulting from strength design is lower than the stiffness required to prevent aeroelastic divergence.

SYMBOLS

a.c.	aerodynamic center
A	aspect ratios, b^2/S
b	wing span, in. (see figure 2)
B_r	width of wing box beam at root section, in.
c	chord (measured perpendicular to elastic axis), in.
c_r	root chord, in. (see figure 2)
c_t	tip chord, in. (see figure 2)
$\bar{c}$	average chord, $(c_r + c_t)/2$, in.
$C_{L_{\alpha_e}}$	effective lift-curve slope per radian
e.a.	elastic axis
E	Young's modulus of elasticity, lb./sq. in.
$(EI)_r$	wing bending stiffness at root, lb. in^2
F.S.	front spar
F_b	allowable bending stress, lb./sq. in.
h_r	wing thickness at root, in.
I	section bending moment of inertia, in.^{4}
L	distance on wing semi-span along elastic axis from root to tip, in.
M	bending moment about an axis perpendicular to elastic axis, at wing root, in.-lb.
M_o	free-stream Mach number
n	maneuver load factor, 3.75g ultimate
q	dynamic pressure, lb./sq. ft.
q(des)	design divergence dynamic pressure, lb./sq. ft.
$\bar{q}$	dimensionless dynamic pressure
R.S.	rear spar

S	total wing area, sq. in.
W	design gross weight, lb.
Λ	angle of wing sweep at elastic axis, deg.

DISCUSSION

General

Estimation of the upper limits in aspect ratio depend on the determination of a required wing box stiffness to prevent divergence and the maximum available wing box stiffness. The charts and approximate formulas from Reference 2 are used to estimate the required bending stiffness as a function of aspect ratio for a given dynamic pressure and aircraft size. Simple engineering beam theory and the assumption of a solid aluminum alloy section at the wing root is used to determine the maximum available stiffness as a function of aspect ratio and the stiffness associated with maneuver strength design.

A conventional hollow shell type structure might have been assumed for the wing box and computations made with little additional effort, but the choice of a reasonable limitation in upper and lower effective cover thicknesses is a matter of arbitrary choice. The objective is to determine an optimistic maximum upper limit of aspect ratio for a given aircraft size.

Criteria

The following criteria were provided for this study:

(1)	Design gross weight	= 200,000 pounds
(2)	Wing area	= 2000 sq. ft.
(3)	Oblique wing angle	= 45 degrees
(4)	Design Mach number	= 1.5
(5)	Design altitude	= 29,000 ft.
(6)	Design divergence dynamic pressure (includes a 1.15 factor on speed)	= 1368 lb./sq. ft.
(7)	Wing taper ratio	= .50
(8)	Wing thickness (h/c)	= 11% and 15%
(9)	Ultimate maneuver load factor	= 3.75g
(10)	Structural material is an aluminum alloy	
(11)	Distance between the elastic axis and the aerodynamic center is zero	

Figure 2 is a wing definition showing the position of the wing in relation to the centerline of the airplane fuselage. It also defines the basic geometry of the wing planform and wing box section at the root. For simplicity the root section is taken at the fuselage centerline.

The load diagram shown in Figure 3 depicts the assumed elliptical wing load distribution which is used in the calculation of bending stiffness associated with maneuver load strength design.

Analysis

Figures 4 and 5 present the results of the analysis which follows. Shown in Figure 4 is a straight line which defines a linear variation of wing root bending stiffness with aspect ratio required to prevent divergence of the leading half of the oblique wing at the design conditions. The basis of this line is an equation taken from Reference 2 which assumes that the wing chord varies linearly and the spanwise distribution of bending stiffness varies as the fourth power of the chord. The following derives the equation of the line:

From Reference 2, page 4:

$$\bar{q} = \frac{q}{144} \; \frac{C_{L_{\alpha_e}} c_r L^3 \sin\Lambda}{(EI)_r}$$

where

$q = q(\text{des}) = 1368$ lb./sq. ft.

$$C_{L_{\alpha_e}} = \frac{4\cos\Lambda}{\sqrt{M_o^2\cos^2\Lambda - 1}} = .8$$

$\bar{q} = 3.6$ for $c_t/c_r = .5$ (Reference 2, Figure 2e)

$A = b^2/S = (2L\cos\Lambda)^2 \,/\, S$

$L = \sqrt{A\,S/2} = 379.473\sqrt{A}$ in.

$\bar{c} = S/2L$

Substituting the expression for L into the expression for $\bar{c}$ and solving for c_r:

$\bar{c} = \sqrt{S/2A}$ in.

$c_r = 4\bar{c}/3 = \sqrt{8S/9A} = 505.964 \,/\, \sqrt{A}$ in.

Substituting the above values in the equation for $\bar{q}$ and solving for the root bending stiffness, yields:

$(EI)_r = 412.673 \times 10^9 A$ lb./sq. in.

The cruved lines in Figures 4 and 5 define the variation of available wing root bending stiffness, $(EI)_r$, with aspect ratio for two solid aluminum alloy sections. The section is assumed to be located at the centerline of the airplane.

These curves are to provide an indication of upper boundaries in available wing stiffness for two wing thickness ratios (h/c) of 11% and 15%. Referring to Figure 2 and assuming h_r constant across the box width, the bending stiffness of a solid rectangular section at the wing root is:

$$(EI)_r = EB_r h_r^3/12$$

where

$$E = 10^7 \text{ lb./sq. in.}$$

$$B_r = .48c_r = .48(505.964)/\sqrt{A} = 242.863/\sqrt{A} \text{ in.}$$

$$h_r = (h/c)c_r = (h/c)505.964/\sqrt{A} \text{ in.}$$

For $h/c = .11\ c_r$

$$h_r = 55.656/\sqrt{A} \text{ in.}$$

$$(EI)_r = 34891 \times 10^9/A^2 \text{ lb./sq. in.}$$

For $h/c = .15\ c_r$

$$h_r = 75.895/\sqrt{A} \text{ in.}$$

$$(EI)_r = 88473 \times 10^9/A^2 \text{ lb./sq. in.}$$

Each horizontal line in Figure 5 defines the wing root bending stiffness, $(EI)_r$, associated with the required strength for an assumed elliptical load distribution. The distribution shown in Figure 3 includes a 20% inertial load relief resulting from a 3.75g vertical acceleration maneuver load factor. As shown in Figure 5, $(EI)_r$ is constant for all aspect ratios for each value of h/c. The derivation is as follows:

$$M = 2/3\ LWn/\pi \quad \text{(see Figure 2)}$$

$$W = 200{,}000 \text{ lb.}$$

$$n = 3.75g \text{ ult.}$$

$$L = 379.478\sqrt{A}$$

Substituting in the above equation for M

$$M = 48.316 \times 10^6 \sqrt{A} \text{ in.-lb.}$$

Assuming simple beam theory at the root section

$$F_b = MC/I = 50{,}000 \text{ lb./sq. in.}$$

$$c = h_r/2 \text{ in.}$$

$E = 10^7$ lb./sq. in.

Then $(EI)_r = 100\ Mh_r = 4831.6 \times 10^6\ h_r \sqrt{A}$

For $h/c = .11\ c_r$

$$h_r = 55.656/\sqrt{A}$$

$$(EI)_r = 268.91 \times 10^9 \text{ lb./sq. in.}$$

For $h/c = .15\ c_r$

$$h_r = 75.895/\sqrt{A}$$

$$(EI)_r = 366.69 \times 10^9 \text{ lb./sq. in.}$$

Results

Figures 4 and 5 show the variations in the available wing box root bending stiffness as a function of aspect ratio for two thickness-to-chord ratios of 11 and 15 percent. The box cross sections are assumed to be solid aluminum alloy rectangular sections. Figure 4 includes the linear variation of the required bending stiffness at the root to prevent aeroelastic divergence. The intersections of the required divergence stiffness line with the available solid section stiffness curves indicate the maximum aspect ratio wing possible for each of two wing to thickness ratios and the assumed aircraft weight, geometry, and operating requirements. Similarly, Figure 5 indicates the maximum possible aspect ratio wings based on strength design for two solid aluminum alloy wing box sections. A comparison of the wing box root stiffness levels shown in Figures 4 and 5 indicates that the wing box is divergence stiffness critical rather than strength critical for all reasonable aspect ratios. Indicated in Figure 4 are maximum wing aspect ratios of about 4.4 and 6 for thickness ratios of 11 and 15 percent, respectively.

CONCLUSION

Figures 4 and 5 indicate that the wing box structure will be stiffness rather than strength critical. With wing thickness ratios of 11 and 15 percent, the maximum permissible aspect ratios are 4.4 and 6. These values are for a solid aluminum alloy section and will be lower for reasonable designs.

The low aspect ratios may be increased by increasing the wing thickness and/or by utilizing materials with higher moduli of elasticity and rigidity. Examples of such materials are: steel, titanium and advanced composite materials of graphite-epoxy, boron-epoxy or graphite-aluminum.

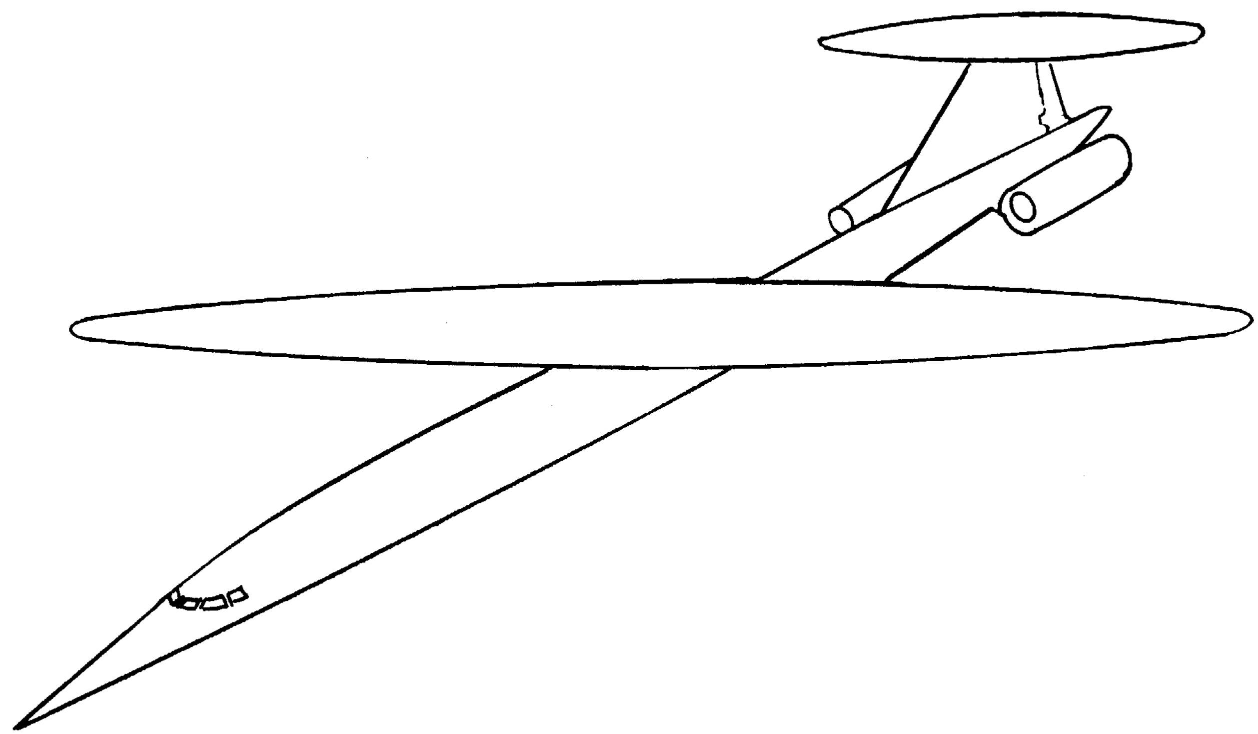

FIGURE 1 OBLIQUE WING AIRPLANE CONCEPT

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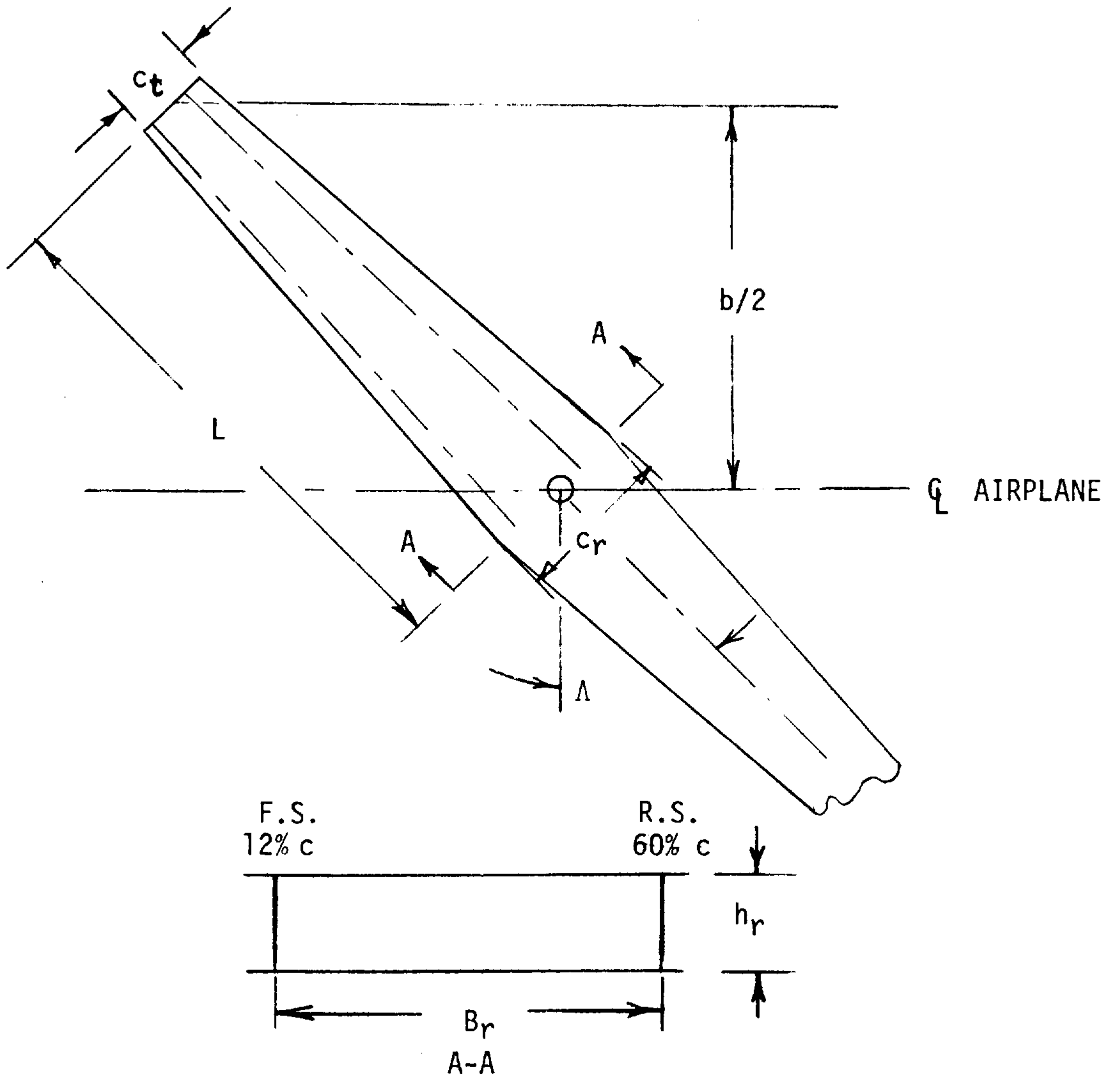

FIGURE 2 - WING DEFINITION

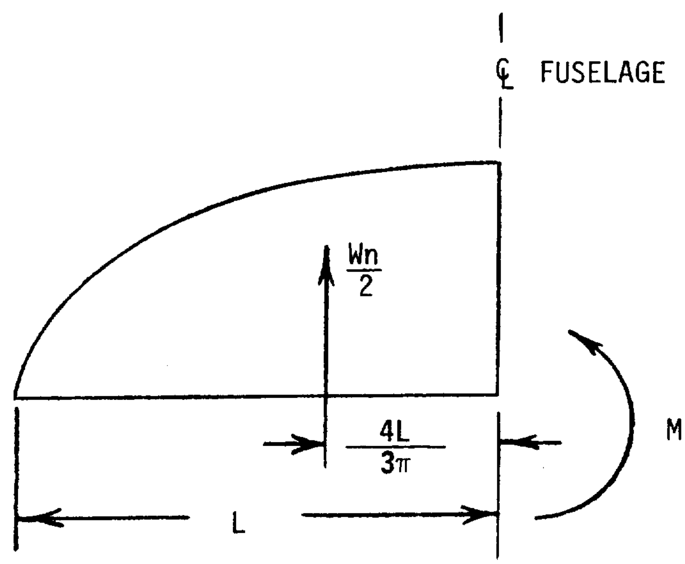

FIGURE 3 - LOAD DIAGRAM

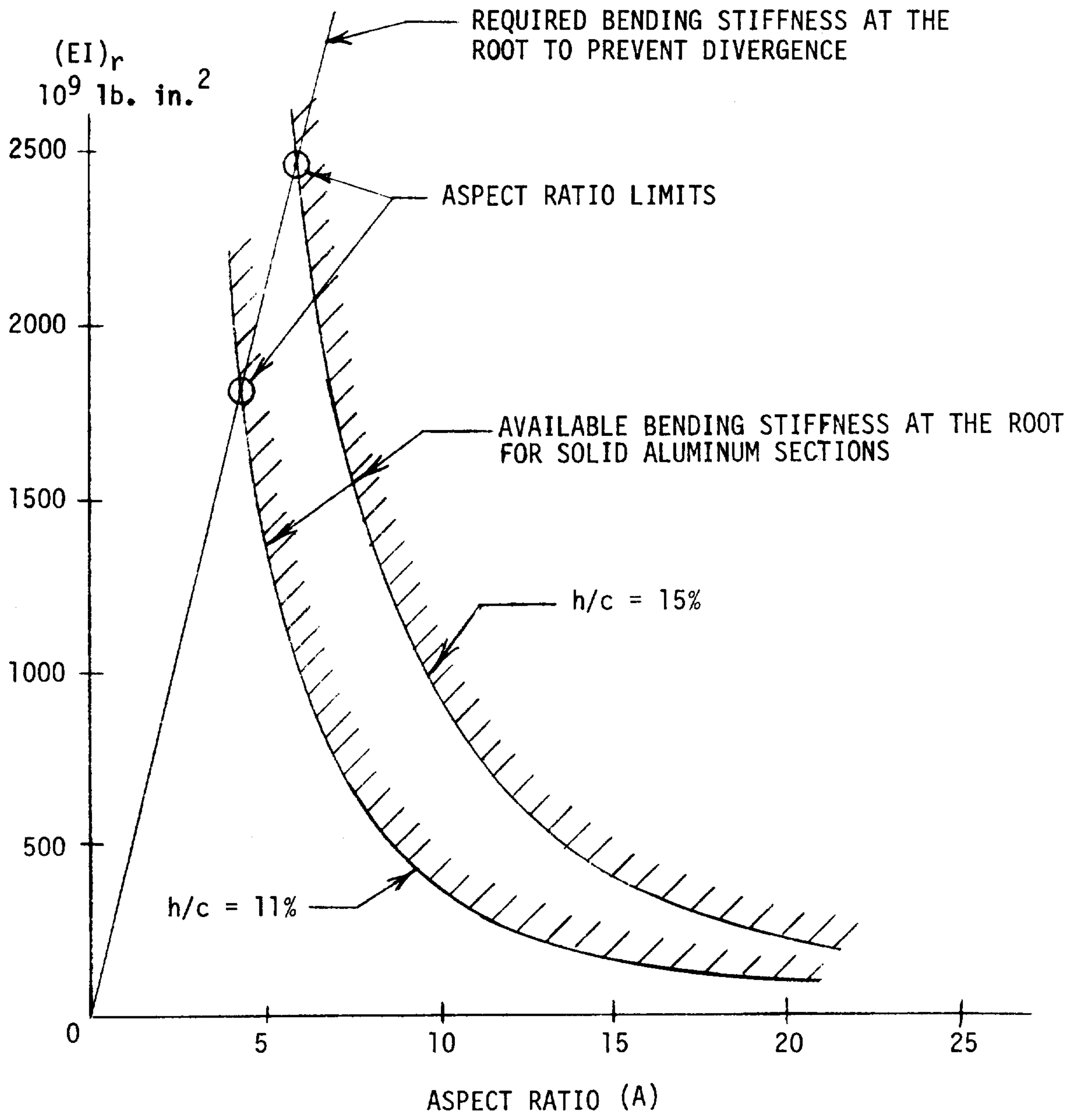

FIGURE 4. ASPECT RATIO LIMITS FOR DIVERGENCE STIFFNESS DESIGN

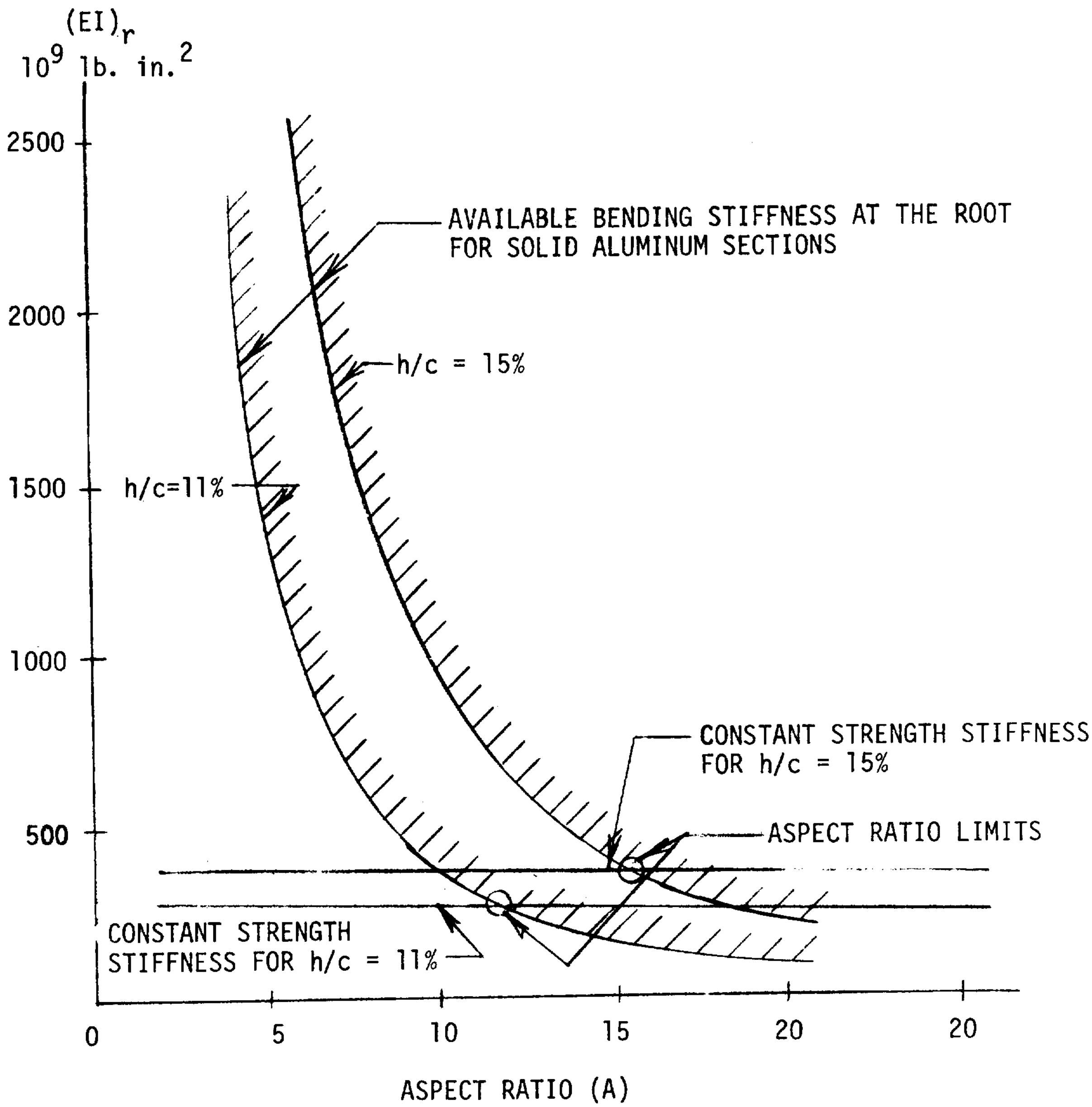

FIGURE 5. ASPECT RATIO LIMITS FOR STRENGTH DESIGN

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